ULTRASHORT PULSES IN MULTICOMPONENT MEDIA AND PHOTONIC BANDGAP STRUCTURES

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by

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13. ABSTRACT The mathematical algorithms and programs for the study of the resonant light-matter interactions in the multi-component and multilevel media and photonic bandgap structures have been developed. The optimal component distribution in the two-component media have been found to get a pulse of a superradiative emission of the highest intensity. The mathematical algorithms and programs for the study of the femtosecond pulse propagation in an extended medium of the two-level atoms have developed. The regime of the inversionless superradiance in the two-component superradiative medium has been investigated. The theory of the superradiance by an ensemble of the two-level atoms embedded in the dielectric host was developed. It was shown that the near dipole-dipole interaction of dense collection of two-level atoms is enhanced by the presence of the host material, decreasing the pulse temporal width and increasing the peak pulse intensity of superradiative emission. The theory of nonlinear light-matter interaction in multidimensional resonant photonic crystals under Bragg diffraction condition has been developed. It was obtained the analytical and numerical solutions describing the novel kinds of nonlinear solitary waves: the Laue soliton, 0-field, propagating and standing gap solitary waves. It has been described the spatio-temporal nonlinear dynamics of coherent field in periodic resonant structures with arbitrary modulation of atomic density and gain gratings			
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ULTRASHORT PULSES IN MULTICOMPONENT MEDIA AND PHOTONIC BANDGAP STRUCTURES

In accordance with the contract the main goals of the research were:

a. Study of the specific features of ultrashort pulse propagation and dynamic nonlinear Bragg diffraction in two-and three-dimensional photonic bandgap structures;

b. Develop methods for the control of pulse duration and shape and;

c. Investigate coherent methods of the ultrashort pulse formation, based on the coherent interactions in multi-component media and photonic bandgap structures.

The research included the following phases:

1. The development of the mathematical algorithms and computations for the Maxwell-Bloch equations in the general case of ultrashort pulses to describe a pulse dynamics beyond the slowly varying envelope approximation;
2. The study of the complete set of the Maxwell-Bloch equations with the aim of determining conditions for self-similar pulse propagation;
3. The investigation of the specific features of pulse amplification in the multi-component media and gain grating to define the optimal conditions for coherent pulse compression and amplification;
4. Study of the characteristic properties of the coherent interactions in the three-level atomic media for the development of the methods of pulse parameter control;
5. Exploration of the possibility for self-similar pulse formation during the process of the nonlinear diffraction in the excited photonic bandgap structures and gain grating.

In accordance with the above mentioned goals we have developed the mathematical algorithms for the study of the dynamics of superradiance by the multicomponent media. The developed algorithms enable us to determine the optimal component distribution to get the pulse of the highest intensity and shortest duration. The study of the dynamics of the two-component superradiance has shown that the generation can occur even in the case when the concentration of resonantly absorbing atoms exceeds the concentration of the resonantly amplifying ones. In this case the net population inversion is negative during the whole process of emission. Nevertheless the superradiance pulses with a sufficiently high power and sufficiently short duration can be produced in comparison with the mono-component superradiative media [1].

The specific features of the pulse propagation and amplification in the multicomponent media have been investigated. The results of the computer simulations enable us to find the new type of pulses with the stable pulse area. These pulses propagate in the two-component media in pairs. In dependent on the initial distance between pulses they propagate as a bound pair, colliding pulses or solitary pair [2,3]. The dynamics of such pulse evolution is a demonstration of the new self-organizing processes in the resonant light-matter interactions [4].

The dynamics of the bichromatic field propagation in the media of the three-level atoms or molecules have been investigated. The selfsimilar solutions of this problem have been found in the form of the phasemodulated simulton and Raman solitons [5,6].

We have developed the mathematical algorithms for the study of the dynamics of the femtosecond pulse propagation in the medium of the two-level atoms. The conditions for the generation of harmonics of the incident pulse frequency are determined. The results of preliminary computer simulations enable us to estimate the required parameters for the quasi-continuum emission by the atomic gases.

We have developed the theory of superradiance by a system of the two-level atoms embedded in the dielectric host. The computer simulations based on the generalized Maxwell-Bloch equations show that the near dipole-dipole interaction of dense collection of two-level atoms is enhanced by the presence of the host material, decreasing the pulse temporal width and increasing the peak pulse intensity of superradiative emission. We showed that the inversion-dependent detuning effect appears in the highly dense and thin dielectric medium. This effect manifests itself in the beating of the emitted pulse intensity. This is a specific feature for the systems consisting from the identical two-level atoms. As it was shown earlier that if the superradiative medium consists of two species of the two-level atoms with the different dipole moments of the resonant transitions than the detuning between the two components can result in the increase of the peak pulse intensity. Therefore the incorporation of the local-field effects into the theory of the two-component superradiance demonstrate the benefits of the two-component solid state superradiative medium [10].

We investigated the spatial-temporal nonlinear dynamics of formation and propagation of ultrashort optical pulses in resonant photonic crystals [7-9,12]. The equations of nonlinear dynamic diffraction for general case of two-wave diffraction problem in multidimensional periodic resonant structures have been derived from the semiclassical Maxwell-Bloch equations describing the coherent light-matter interaction under Bragg condition. It has been created the computer program to carry out the numerical simulation of nonlinear diffraction under different boundary conditions. By means of analytical and numerical integration of the equations we have studied the process of formation and propagation of Bragg solitary waves for the different geometric schemes of diffraction. It has been shown that nonlinear solitary waves appear both in the case of Bragg and Laue geometry of diffraction. In the first case the nonlinear resonant interaction leads to arising of propagating gap solitary waves as well to the formation of standing Bragg waves and coherent inverse population grating in the structure. In the case of the Laue diffraction the incident field does not reflect at the sample boundary, because there is no the Bragg band gap for transmitting field. Two diffracted modes are coupled due to reflection on the crystallographic planes within structure. We have obtained exact expression for novel kind of coupled-mode soliton. It is a Laue soliton which propagates in the direction of the normal to reciprocal lattice vector. Computer simulation allows to investigate the process of Laue soliton formation from incident field, and furthermore, the possibility of arising of so called "0-field" [12]. This field consists of two coupled diffracted modes with opposite singes of amplitudes, so the sum of the mode amplitudes is equal to zero. As a result, the total 0-field with large partial mode amplitudes propagates through the resonant structure like linear field without nonlinear interaction with two-level atoms.

It has been predicted earlier that the gap soliton of self-induced transparency propagates at the Bragg frequency in discrete resonant structure, which consist of a set of ultrathin layers of two-level atoms [10]. We considered theoretically the short pulse transmission in a resonant one-dimensional Bragg structure with arbitrary periodic modulation of atomic density. This model could be realized, for instance, in experiments with colloidal crystals. It has been found the analytical and numerical solutions of Maxwell-Bloch equations, which describe the spatio-temporal dynamics of gap solitary wave formation and propagation in the case when the frequency is in the linear forbidden gap band of arbitrary resonant periodic Bragg structure. The velocity and form of the pulse depends on the profile of atomic density modulation. The pulse propagation in sinusoidal structure is similar to the case of discrete Bragg structure. We studied also the coherent decay of optically-written sinusoidal gain grating under Bragg condition. Describing this process by numerical solution of coupled-mode Maxwell-Bloch equations we investigated the dependence of the spatio-temporal dynamics of field and inverse population of

atoms on frequency shift and initial inverse population. The coherent interaction of incident pulse with the gain grating leads to its amplification and shortening.

List of publications:

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3. Andreev A.V, Polevoy P.V. «Coupled pulses propagation in two-component media». ICONO'98 Technical Digest (URSS Publ., Moscow 1998), p.320.

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1. Andreev A.V., Prof.	\$2200
2. Mantsyzov B.I., Dr.	\$1650
3. Polevoy P.V., Dr.	\$1100
4. Khachaturov R.V., Dr.	\$1100
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Specific Features of Superradiance in Two-Component Media

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Abstract—Specific features of superradiance in two-component media are discussed. It is demonstrated that the adoption of a resonantly absorbing component into a superradiant medium opens up new opportunities to control the parameters of superradiance pulses.

1. INTRODUCTION

Superradiance is a collective coherent spontaneous decay of a system of excited atoms or molecules. This phenomenon was predicted by Dicke [1] in 1954. It was demonstrated that the growth in the number density of excited particles increases the rate of radiative spontaneous decay, and incoherent decay, when radiation intensity is proportional to the number of excited particles N ($I_{SP} \sim N$), is replaced by coherent spontaneous decay—superradiance. The intensity of superradiance is proportional to the number of excited particles squared ($I_{SR} \sim N^2$). Consequently, in a macroscopic system, when $N \gg 1$, coherent radiation is much stronger than incoherent radiation. In the first experiment [2, 3], the superradiance intensity was higher than the intensity of ordinary spontaneous emission by a factor of more than 10^{10}.

Investigation of superradiance in gas media [4–7] and metal vapors [8–10] can be considered as the first stage of the experimental confirmation of the theory of superradiance. In first experiments, the density of excited atoms or molecules fell within the range $n_0 = 10^{10}$–10^{12} cm^{-3}. Subsequently, the density of excited particles was increased by two to three orders of magnitude. At the next stage, superradiance from solids, where $n_0 \approx 10^{16}$ cm^{-3}, has been studied [11, 12].

Initially, superradiance was considered as a method of cavity-free lasing, since there were no mirrors on the boundaries of active superradiant media, and even cell ends were cut at a Brewster angle. However, currently, the theory of superradiance in an optical cavity [13, 14], the theory of mode superradiance [15], and the theory of superradiance in two-component media [16–20] are being developed. Two-component media are of great interest for the generation of high-power short coherent pulses [16–18, 20]. Superradiance pulses from two-component media are characterized by considerable delay times, appreciably exceeding the durations of superradiance pulses, which may allow us to substantially loosen requirements to the duration of the pumping pulse [17]. The feasibility of the experimental implementation of two-component superradiance and the problems associated with the choice of resonant media are discussed in [20]. The specific features that distinguish two-component media from one-component media are due to more versatile dynamics of pulse generation and amplification [16, 21] in two-component media. Therefore, two-component media exhibit the regimes, e.g., subthreshold pulse amplification [22] or superradiance without inversion, considered in this paper, that cannot arise in one-component media. Therefore, the investigation of the properties of two-component media and the application of such media provide an opportunity to propose new methods of lasing and compression of short coherent pulses.

2. FORMULATION OF THE PROBLEM

Let us investigate the dynamics of superradiance in a medium that consists of atoms of two sorts, a and b, with different values of the transition dipole moment, $d_a < d_b$. Since the Rabi frequency is proportional to the magnitude of the transition dipole moment, $\Omega \sim d$, we have $\Omega_a < \Omega_b$. Atoms with a higher Rabi frequency (atoms of the b sort) will be referred to as fast atoms, whereas atoms of the a sort will be referred to as slow atoms. We also assume that atoms in the two-component medium satisfy the resonance conditions (Fig. 1), i.e., the relation

$$\omega_b = \omega_a + \Delta, \quad |\Delta| \ll \omega_a, \omega_b, \tag{1}$$

is met for the relevant transition frequencies.

We consider a two-component medium where fast atoms initially reside in the ground state and slow atoms are excited by a pumping pulse with a finite duration.

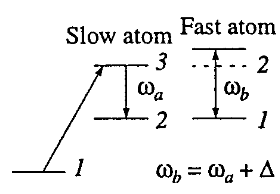

Fig. 1. Energy diagram of the levels of slow and fast atoms in a two-component medium.

The generation process in such a medium is governed by a set of Maxwell–Bloch equations for slowly varying envelopes of counterpropagating waves ($a_{1,2}$), polarizations of fast ($p_{1,2}$) and slow ($P_{1,2}$) atoms, and population differences between the levels 2 and 1 (r) for fast atoms and levels 3 and 2 (R) for slow atoms [16]:

$$
\begin{aligned}
\frac{\partial a_1}{\partial t}+\frac{\partial a_1}{\partial x} &= P_1+p_1+Q_0\frac{1+R}{2}+q_0\frac{r_0+r}{2},\\
\frac{\partial a_2}{\partial t}-\frac{\partial a_2}{\partial x} &= P_2+p_2+Q_0\frac{1+R}{2}+q_0\frac{r_0+r}{2},\\
\frac{\partial P_1}{\partial t}+\alpha_a P_1 &= \beta_a a_1 R,\\
\frac{\partial P_2}{\partial t}+\alpha_a P_2 &= \beta_a a_2 R,\\
\frac{\partial p_1}{\partial t}+(\alpha_b+i\Delta)p_1 &= \beta_b a_1 r,\\
\frac{\partial p_2}{\partial t}+(\alpha_b+i\Delta)p_2 &= \beta_b a_2 r,\\
\frac{\partial R}{\partial t} &= -(a_1P_1+a_2P_2)+\frac{1}{\sqrt{\pi}}\frac{1}{\tau_{\text{pump}}}\exp\left\{-\frac{(t-t_0)^2}{\tau_{\text{pump}}^2}\right\},\\
\frac{\partial r}{\partial t} &= -(a_1p_1+a_2p_2).
\end{aligned}
\tag{2}
$$

The field amplitude $a(x, t)$ in the set of equations (2) is normalized in such a manner that $n(x, t) = |a(x, t)|^2$ is the quantum number density expressed in units of the density of slow atoms, $n_a = N_a/V$. The population of slow atoms varies within the range $-1 \le R \le 1$, whereas the population of fast atoms varies within the range $-r_0 \le r \le r_0$. In other words, the amplitude of population variation for fast atoms is determined by the ratio of component concentrations: $r_0 = N_b/N_a$.

The model described above demonstrates a good agreement between the results of numerical simulation [17] and the data of real physical experiments [23] in the case of a one-component medium.

3. THE MAIN RESULTS

Numerical simulation shows that the spatiotemporal dynamics of superradiance in a two-component medium qualitatively differs from the dynamics of superradiance in a one-component medium [16, 17]. In a one-component medium, generation starts at the boundary of the active medium. Then, generation evolves toward the inside of the medium. In a two-component medium, generation arises inside the medium, which increases the efficiency of the release of the energy stored in the medium.

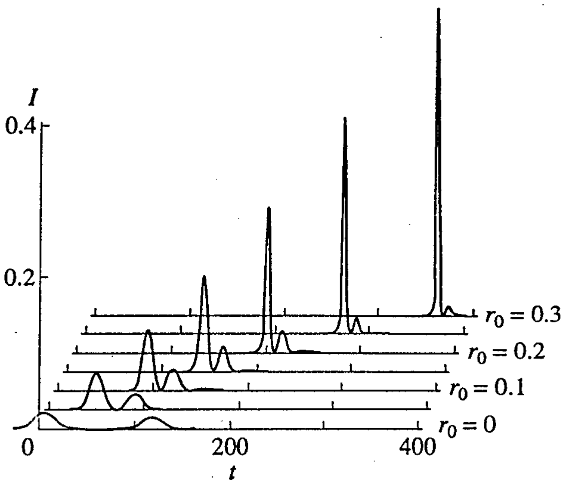

Fig. 2. Intensity profiles of superradiance pulses in a two-component medium for different concentrations of fast atoms.

These effects are illustrated by Fig. 2, which displays the intensity profiles of superradiance pulses in a two-component medium plotted for different concentrations r_0 of fast atoms. The first generation pulse arises in a medium where $r_0 = 0$. In other words, this pulse is a pulse of superradiance of a one-component medium. As can be seen from Fig. 2, adding fast resonant atoms that initially reside in the ground state to a superradiant medium, one can considerably increase the peak intensity of superradiance pulses and simultaneously reduce their duration. Thus, Fig. 2 clearly demonstrates that the intensity of two-component superradiance may be substantially higher than the intensity of one-component superradiance.

Evidently, the growth in the density of fast atoms increases absorption in the medium and, therefore, cannot give rise to a permanent growth in the intensity of superradiance pulses. When the concentration of fast atoms becomes higher than a certain threshold [16, 17], generation in a two-component medium becomes impossible. Thus, two-component superradiance has a threshold character. However, the threshold concentration of fast atoms r_{th} may vary, depending on the parameters of a two-component medium. In particular, the value of r_{th} can be made large [18, 19]. In such a situation, the regime of superradiance without inversion becomes possible.

Figure 3 displays the intensity (Fig. 3a) and duration (Fig. 3b) of superradiance pulses in a two-component medium as functions of the concentration of fast atoms. Recall that the normalization was introduced in such a manner that the concentration of fast atoms is expressed in units of the number of slow atoms.

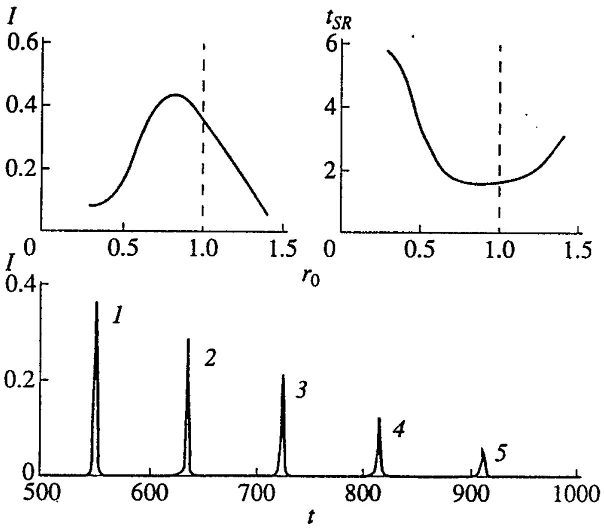

Fig. 3. (a) Intensity and (b) duration of superradiance pulses in a two-component medium as functions of the concentration of fast atoms. (c) Intensity profiles of superradiance pulses for different concentrations of fast atoms: (*1*) $r_0 = 1.0$, (*2*) 1.1, (*3*) 1.2, (*4*) 1.3, and (*5*) 1.4.

Consequently, the equality $r_0 = 1$ implies that the concentrations of slow and fast atoms are equal to each other in a two-component medium. Vertical dashed lines in Fig. 3 indicate the value $r_0 = 1$. At this point, the concentration of slow atoms is equal to the concentration of fast atoms, and the net population difference $(R_0 - r_0)$ is equal to zero. As can be seen from Fig. 3, generation can arise in a two-component medium even when the number of resonant atoms in the ground state is greater than the number of excited resonant atoms. Note that, in the range $r_0 > 1$, where the concentration of atoms in the ground state is greater than the concentration of excited atoms, and the total population difference in a two-component medium is negative, $(R_0 - r_0) < 0$, superradiance pulses with a sufficiently high power and sufficiently short duration can be produced within the entire generation process.

The regime considered above can be referred to as superradiance without inversion. Figure 3c displays the intensity profiles of superradiance pulses for various concentrations r_0 of fast atoms. As can be seen from Fig. 3c, the pulses of two-component superradiance are characterized by considerable delay times, which appreciably exceed the duration of these pulses. Although the intensity of superradiance pulses lowers with the increase in the concentration of the fast component in the range $r_0 > 1$, the intensity of such pulses is comparable with the maximum intensity, which is achieved in the case under study when $r_0 \approx 0.75$.

Note that the situation considered above is not optimal. Varying parameters of two-component media, one can further increase the peak intensity of the generated pulses and reduce their duration [18, 19].

The insertion of a two-component inhomogeneously broadened superradiant medium into an optical cavity [24] opens up broad opportunities in controlling parameters of superradiance pulses. In the case of cavity-free superradiance, two pulses propagating along the active medium in opposite directions are produced. We can accumulate the energy of two pulses of cavity-free superradiance in a single superradiance pulse by implementing a cavity with a single totally reflecting mirror. In such a situation, due to the coherence of interaction, the peak intensity will be increased at least by a factor of four, and the duration of the cavity superradiance pulse will be reduced. Varying the configuration of the optical cavity, parameters of inhomogeneously broadened two-component media [24], and the distribution of the fast component, one can increase the intensity of the generated pulses. Thus, two-component media provide an opportunity to produce superradiance pulses with much higher power and much shorter duration than in the case of conventional one-component media. Therefore, the investigation of the properties of two-component media opens up new opportunities in controlling the parameters and the waveform of the generated pulses.

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Influence of local-field effects on the dynamics of superradiance by dense medium

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ABSTRACT

The theory of superradiance by an ensemble of two-level atoms embedded in a dielectric host is developed. It is shown that the near dipole-dipole interaction of a dense collection of two-level atoms is enhanced by the presence of the host material, decreasing the pulse temporal width and increasing the peak pulse intensity of superradiative emission. The influence of the inversion-dependent detuning effect on the parameters of the emitted pulses is investigated.

Keywords: superradiance, local field, multicomponent media

1. INTRODUCTION

Most of the theory of superradiance [1] deals with atomic and molecular gas media or metal vapors [2-4]. The atomic or molecular density in this case is small and lies in the range $(10^9\text{-}10^{14})\mathrm{cm}^{-3}$, therefore we can neglect the local-field effects, because the mean distance between the particles is greater than the wavelength of radiation. The situation is drastically changed if we deal with the solid state superradiative [5,6] or superfluorescent [7] medium. In this case the presence of the linearly polarizable host changes the local field at the resonant atoms. The macroscopic field E and local field E_L are related by well known Lorentz equation [8]

$$E_L = E + \frac{4\pi}{3} P \tag{1}$$

where P is the volume polarization due to the host material and resonant atoms.

2. MAIN EQUATIONS

By taking into account this relationship we should modify the Maxwell-Bloch equations describing the interaction of the coherent electro-magnetic wave with an ensemble of the two-level atoms [9-11].

Here we study the dynamics of superradiative decay by an ensemble of the two-level atoms embedded in the crystal host. It is assumed that the dielectric function of the host can be represented by a complex constant. This assumption is met when the wave emitted by the superradiative two-level atoms is far from resonance with the host material. Also we assume that the active volume has a pencil-like form with a Fresnel number about unity. Therefore, consistent with the plane wave approximation, we can use one dimensional equations for the vector potential amplitudes ($A_{F,B}(x,t)$) of counterpropagating electro-magnetic waves, the resonant transition current density amplitudes ($J_{F,B}(x,t)$) associated with these electro-magnetic waves, and population inversion density ($R(x,t)$). In the slowly varying envelope approximation [12] the equations of motion accounting the local field effects [10,11] are

$$\frac{\partial R_0}{\partial t} = -\frac{1}{2\hbar c}\,(f^* A_F^* J_F + f\, A_F J_F^* + f^* A_B^* J_B + f\, A_B J_B^*) \tag{2a}$$

$$- (f^* - f)\,\frac{2\pi i}{3\hbar\omega^2}\,(|J_F|^2 + |J_B|^2) - \gamma_\parallel (R_0 - R_{eq})$$

$$\frac{\partial R_1}{\partial t} = -\frac{1}{2\hbar c}\,(f^* A_B^* J_F + f\, A_F J_B^*) - (f^* - f)\,\frac{2\pi i}{3\hbar\omega^2}\, J_B^* J_F \; - \gamma_\parallel R_1 \tag{2b}$$

$$\frac{\partial J_F}{\partial t} = i\,(\Delta - \frac{4\pi}{3\hbar}|\mu|^2 f\, R_0)\, J_F + \frac{\omega^2|\mu|^2 f}{\hbar c}(A_F R_0 + A_B R_1) - i\frac{4\pi}{3\hbar}|\mu|^2 f\, J_B R_1 - \gamma_\perp J_F \tag{2c}$$

$$\frac{\partial J_B}{\partial t} = i\,(\Delta - \frac{4\pi}{3\hbar}|\mu|^2 f\, R_0)\, J_B + \frac{\omega^2|\mu|^2 f}{\hbar c}(A_B R_0 + A_F R_1^*) - i\frac{4\pi}{3\hbar}|\mu|^2 f\, J_F R_1^* - \gamma_\perp J_B \tag{2d}$$

$$\frac{\partial A_F}{\partial t} + \frac{c}{\sqrt{\varepsilon_r}}\frac{\partial A_F}{\partial x} = \frac{2\pi c f}{\omega\, \varepsilon_r}\, J_F - \frac{\omega}{2}\frac{\varepsilon_i}{\varepsilon_r} A_F \tag{2e}$$

$$\frac{\partial A_B}{\partial t} - \frac{c}{\sqrt{\varepsilon_r}}\frac{\partial A_B}{\partial x} = \frac{2\pi c f}{\omega\, \varepsilon_r}\, J_B - \frac{\omega}{2}\frac{\varepsilon_i}{\varepsilon_r} A_B \tag{2f}$$

where $\Delta = \omega - \omega_a$ is the detuning of the field carrier frequency ω from the atomic resonance frequency ω_a, μ is the matrix element of the transition dipole moment, $\gamma_\parallel$ and $\gamma_\perp$ are the longitudinal and transverse relaxation rates, respectively, and

$$f = \left(\frac{\varepsilon + 2}{3}\right) \tag{3}$$

is a local-field enhancement factor due to the presence of the linear dielectric host of complex dielectric constant $\varepsilon = \varepsilon_r + i\varepsilon_i$. Note that Eq. (2b) stems from the coupling of the forward (subscript F) and backward (subscript B) field amplitude and polarization waves which are coupled via the inversion density $R = R_0 + R_1\, e^{2ikx} + R_1^*\, e^{-2ikx}$. If we neglect coupling of the forward and

backward waves [13], and assume that the superradiance decay time is much shorter than the independent atom radiative lifetime, Eqs. (2) become

$$\frac{\partial R_0}{\partial t}=-\frac{1}{2\hbar c}(f^* A_F^* J_F+f\, A_F J_F^*+f^* A_B^* J_B+f\, A_B J_B^*)-(f^*-f)\frac{2\pi i}{3\hbar\omega^2}(|J_F|^2+|J_B|^2) \tag{4a}$$

$$\frac{\partial J_{F,B}}{\partial t}+\left(\gamma_\perp-i\,\Delta+i\frac{4\pi}{3\hbar}|\mu|^2 f\, R_0\right) J_{F,B}=\frac{\omega^2|\mu|^2 f}{\hbar c}A_{F,B}\, R_0 \tag{4b}$$

$$\frac{\partial A_{F,B}}{\partial t}\pm\frac{c}{\sqrt{\varepsilon_r}}\frac{\partial A_{F,B}}{\partial x}=\frac{2\pi c f}{\omega\,\varepsilon_r}J_{F,B}-\frac{\omega}{2}\frac{\varepsilon_i}{\varepsilon_r}A_{F,B} \tag{4c}$$

In the wave equation, Eq. (4c), the positive sign is associated with the forward propagating wave A_F and the negative sign is associated with the backward propagating wave A_B.

For numerical calculations, it is expedient to scale Eqs. (4) such that

$$\frac{\partial R_0}{\partial t'}=-\frac{1}{2}(f^* a_F^* j_F+f\, a_F j_F^*+f^* a_B^* j_B+f\, a_B j_B^*)-\frac{i}{3}\frac{(f-f^*)}{\tau\omega}(|j_F|^2+|j_B|^2) \tag{5a}$$

$$\frac{\partial j_{F,B}}{\partial t'}+\left(\gamma_\perp\tau+i\frac{4\pi}{3\hbar}|\mu|^2\tau f\, R_0\right) j_{F,B}=\frac{2\pi\omega^2|\mu|^2\tau^2 f}{\hbar}a_{F,B}\, R_0 \tag{5b}$$

$$\frac{\partial a_{F,B}}{\partial t'}\pm\frac{\partial a_{F,B}}{\partial x}=\frac{f}{\varepsilon_r}j_{F,B}-\frac{\omega\tau}{2}\frac{\varepsilon_i}{\varepsilon_r}a_{F,B} \tag{5c}$$

with $\Delta=0$. In Eqs. (5) we have introduced the dimensionless coordinate x' and dimensionless time t'

$$x'=\frac{x}{L},\qquad t'=\frac{t}{\tau}$$

where

$$\tau=\frac{L\sqrt{\varepsilon_r}}{c}$$

and L is an active volume length. The scaled amplitudes and polarization densities are given by

$$A_{F,B} = S\, a_{F,B}$$

$$J_{F,B} = \frac{c\,\hbar}{S\,\tau}\, j_{F,B}$$

respectively, where

$$S^2 = \frac{2\,\pi\,c\,\hbar}{\omega}.$$

The dimensionless parameters α, β, δ are

$$\alpha = \gamma_{\perp}\tau$$

$$\beta = \frac{2\pi\,\omega\,|\mu|^2\,\tau^2}{\hbar}$$

$$\delta = \frac{2}{3}\frac{f\,\beta}{\omega\,\tau}$$

In the case $f = f^*$ and $\gamma_{\perp}$, the equation of motion for atomic variables produce the well known Bloch integral of motion

$$\sum_{i=F,B} |j_i(x',t)|^2 + 2\,\beta\,R^2(x',t) = 2\,\beta\,R^2(x',0) \tag{6}$$

Note that the range of R is defined by the number density N such that $-N \leq R(x',t) \leq N$. In the computer simulations we use the following boundary conditions

$$a_F(0,t) = a_B(x'=1,t) = 0 \tag{7}$$

In this case the equations of motion for the field amplitudes and population inversion density produce the following equation for the atomic decay rate

$$I(t) = -\frac{\partial}{\partial t}\int_0^1 dx' \left(R(x',t) + \frac{\varepsilon_r}{2}\sum_{i=F,B} |a_i(x',t)|^2 \right) = \varepsilon_r\,|a_F(x'=1,t)|^2 \tag{8}$$

3. COMPUTER SIMULATIONS.

Here we present the results of the computer simulations on the superradiance dynamics by the system of the two-level atoms embedded into the dielectric host. Let us start from the study of the influence of the enhancement factor f on the parameters of the emitted pulses. If we assume that

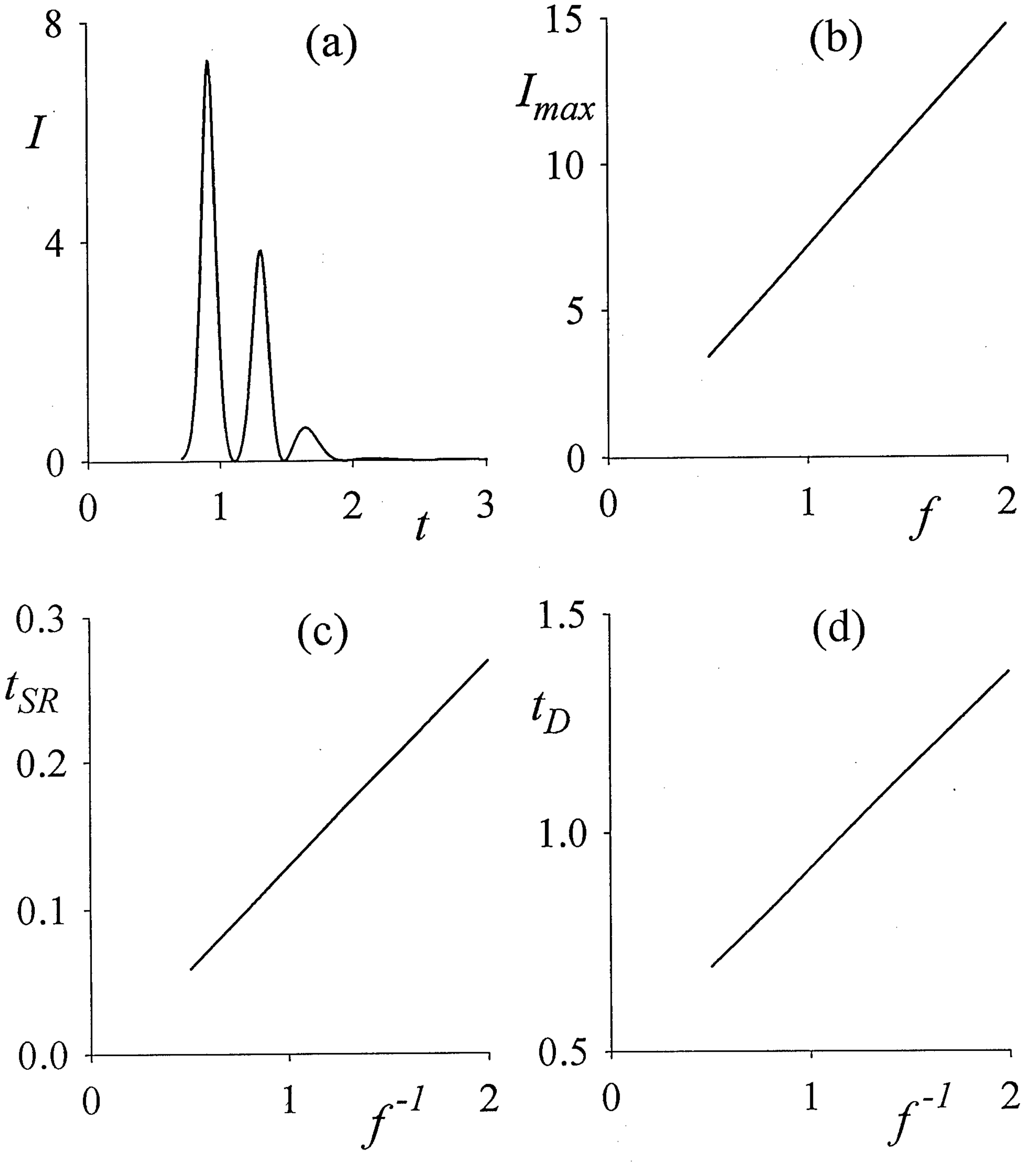

Fig.1 (a) Intensity profile of the superradiance pulse. Peak pulse intensity (b), temporal pulse width (c) and delay time (d) of superradiance pulse as a function of the enhancement factor.

the factor f is a real constant and omit the inversion-dependent detuning term in the generalized Bloch Eqs. (5), then these equations will coincide with the traditional Bloch equations where the amplitude a is substituted by the product of the amplitude and the enhancement factor fa. Fig. 1a shows the profile of the superradiance pulse for the case when the enhancement factor is equal to unity and parameters α and β are $\alpha = 1$, $\beta = 100$. In this case we have the oscillatory regime of superradiance [3], when the emitted intensity has the profile of the damped oscillations. The results of the computer simulations show that the variation in the magnitude of the enhancement factor f retains the oscillatory structure of the emitted pulse but changes the peak pulse intensity (Fig.1b), delay time (Fig.1c) and pulse temporal width (Fig.1d). The peak pulse intensity increases linearly with f, while the delay time and pulse temporal width are inversely proportional to f. Thus the variation in the index of the host enables us to control the emitted pulse parameters.

The second difference in the generalized and traditional Maxwell-Bloch equations consists in the appearance of the inversion-dependent detuning. Fig. 2 shows the superradiance pulse intensity profiles for the different values of the parameter $\delta = 10^{-2}$ (a), 1 (b), 5 (c), 10 (d), 15 (e), 20 (f). It is seen that the peak pulse intensity decreases and pulse temporal width increases with the increase in the magnitude of the parameter δ. The time-dependent detuning distorts the pulse shape. The damped oscillations are now replaced by beating at different frequencies. As a result the pulse temporal spectrum is split and broadened. Notice that in accordance with the Eq. (6) the parameter δ is normally smaller than unity. The effect of the time-dependent detuning becomes important in the relatively thin and highly dense dielectric host.

4. CONCLUSIONS

The theory of superradiance by a system of the two-level atoms embedded in the dielectric host has been developed. The computer simulations based on the generalized Maxwell-Bloch equations show that the near dipole-dipole interaction of dense collection of two-level atoms is enhanced by the presence of the host material, decreasing the pulse temporal width and increasing the peak pulse intensity of superradiative emission. We showed that the inversion-dependent detuning effect appears in the highly dense and thin dielectric medium. This effect manifests itself in the beating of the emitted pulse intensity. This is a specific feature for systems consisting of identical two-level atoms. It was shown in [14-16] that if the superradiative medium consists of two species of the two-level atoms with the different dipole moments of the resonant transitions, then the detuning between the two components can result in the increase of the peak pulse intensity [15]. Therefore the incorporation of the local-field effects into the theory of the two-component superradiance may demonstrate the benefits of the two-component solid state superradiative medium.

ACKNOWLEDGMENTS

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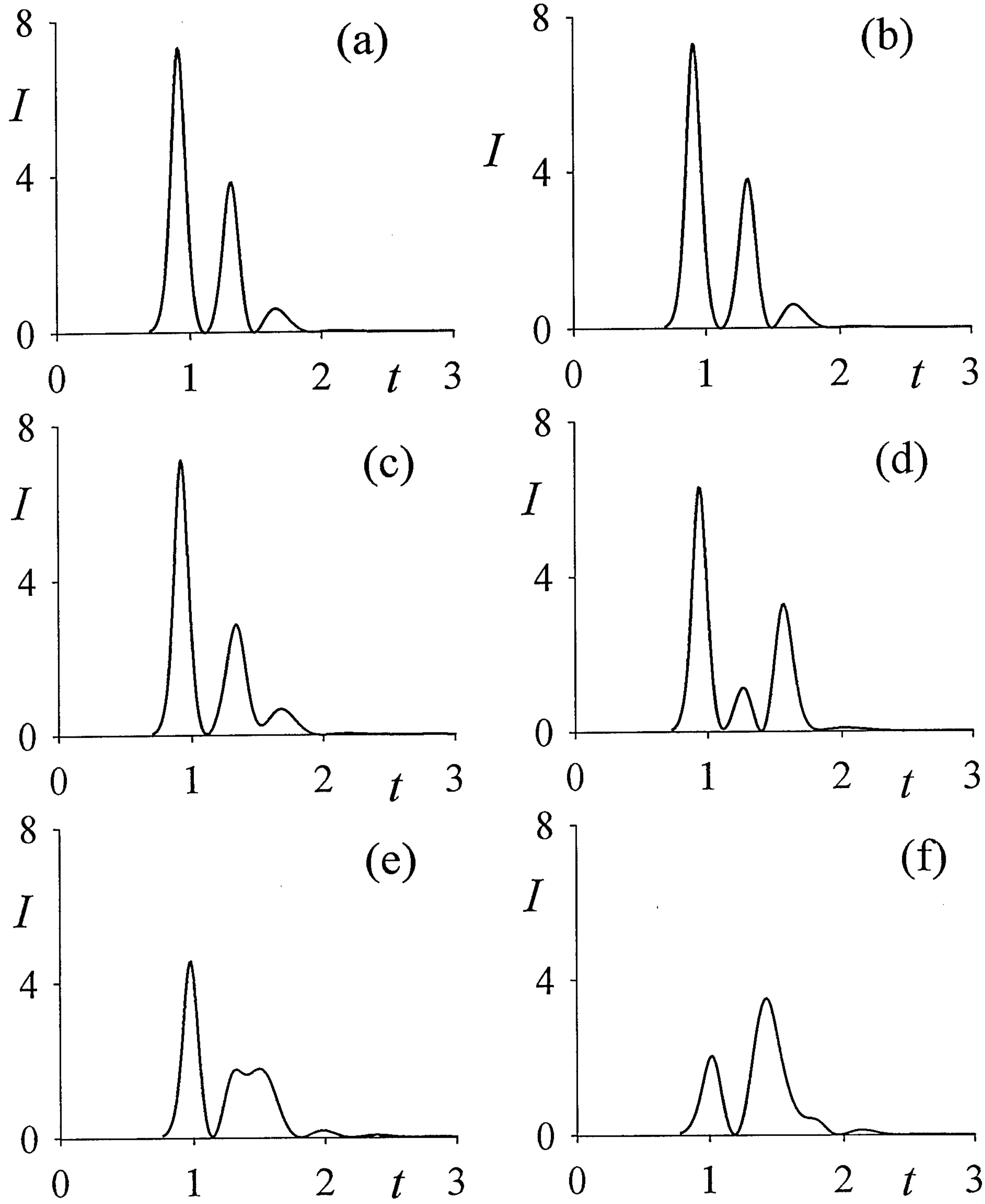

Fig.2. Intensity profiles of the superradiance pulses for different values of the detuning δ=0.01(a), 1(b), 5(c), 10(d), 15(e), 20(f).

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Nonlinear solitary waves in multidimensional resonant photonic bandgap structures

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ABSTRACT

The formation and propagation of nonlinear solitary waves under Bragg condition in multidimensional resonant photonic crystals is described by analytical and numerical solutions of two-wave diffraction Maxwell-Bloch equations. The existence of nonlinear solitary waves both in the Bragg and in the Laue geometry of diffraction has been shown.

Keywords: solitary waves, photonic crystals, resonant interaction, nonlinear Bragg diffraction.

1. INTRODUCTION

The coherent and nonlinear optics of photonic bandgap structures, or photonic crystals, has been at the heart of scientific interest and research in the last years[1]. This is due to the finding of the novel kind of nonlinear solitary waves which are propagated at Bragg frequency within the linear forbidden gap band of the periodic medium. It has been shown that gap solitons and oscillating solitary waves exist in periodical structures with resonant[2,3] and Kerr[4,5] nonlinearity. These waves are formed by two counterpropagating coupled Bragg modes in 1D structures. The progress in a technology allows now to create multidimensional photonic crystals[6]. Several recent investigations on light-matter interaction in these crystals has been carried out for 2D structures of glass[7] and air[8] rods and 3D colloidal crystals[9,10]. Here we study theoretically the dynamics of formation and propagation of nonlinear solitary waves in the general case of two-wave Bragg diffraction problem in 2D and 3D resonant photonic crystals. The vector Bragg condition $\vec{k}_h = \vec{k}_0 + \vec{H}$ for the wave vectors $\vec{k}_0$ and $\vec{k}_h$ of the incident and diffracted waves and the reciprocal lattice vector $\vec{H}$ is to be satisfied in this case. The equations of two-wave nonlinear dynamic diffraction have been derived from the semiclassical Maxwell-Bloch equations describing the coherent light-matter interaction under Bragg condition. By means of analytical and numerical integration of the equations we investigated the process of formation and propagation of Bragg solitary waves for the different geometric schemes of diffraction. It has been shown that nonlinear solitary waves appear both in the case of Bragg geometry of diffraction like gap solitons and in the case of Laue geometry of diffraction like so called two-wave Laue solitons of self-induced transparency. The Laue soliton propagates in the direction of the normal to reciprocal lattice vector. The numerical simulation of diffraction process has given the possibility to study the wave dynamics in a finite medium under different boundary conditions.

2. MAIN EQUATIONS FOR NONLINEAR TWO-WAVE DYNAMIC BRAGG DIFFRACTION

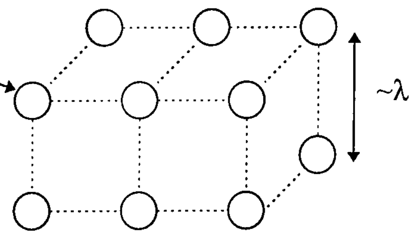
3D photonic crystal in our model is formed by the periodically distributed clusters of resonant two-level atoms (Fig. 1). The period of the lattice is about wave length λ and the cluster size is assumed to be less than λ. Corresponding reciprocal lattice of the crystal is 3D too, but if two wave vectors and reciprocal lattice vector $\vec{H}$ exact satisfy the Bragg condition (Fig. 2)

$$\vec{k}_h = \vec{k}_0 + \vec{H}$$

we are able to replace three-dimensional problem of diffraction by two-dimensional problem using two-wave approximation and taking into account only two strong Bragg modes $E_{o,h}(\vec{r},t)$ of quasimonochromatic field $E(\vec{r},t)$ within the structure

$$E(\vec{r},t) = \frac{1}{2}[E_0(\vec{r},t)\exp(i\vec{k}_0\vec{r} - i\omega t) + E_h(\vec{r},t)\exp(i\vec{k}_h\vec{r} - i\omega t)] + \text{c.c.}$$

cluster of resonant atoms



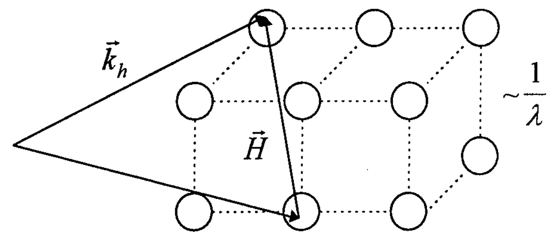


Fig. 1. Distribution of atomic density in 3D resonant crystal.
photonic crystal.
lattice

Fig. 2. Reciprocal lattice of the photonic

Orientation of wave vectors and reciprocal

vector under exact Bragg condition.

To describe the coherent interaction of light with resonant two-level medium the semiclassical approach has been used. Generalizing the Maxwell-Bloch equations of diffraction problem for 1D structure[2] we have derived the following main equations of nonlinear two-wave dynamic Bragg diffraction in resonant 3D photonic crystals:

$$c\frac{\partial\Omega_0(\vec{r},t)}{\partial\vec{k}_0} + \frac{\partial\Omega_0(\vec{r},t)}{\partial t} = \tau_c^{-2}P(\vec{r},t),$$
$$c\frac{\partial\Omega_h(\vec{r},t)}{\partial\vec{k}_h} + \frac{\partial\Omega_h(\vec{r},t)}{\partial t} = \tau_c^{-2}P(\vec{r},t),$$
$$\frac{\partial P(\vec{r},t)}{\partial t} = n(\vec{r},t)[\Omega_0(\vec{r},t) + \Omega_h(\vec{r},t)],$$
$$\frac{\partial n(\vec{r},t)}{\partial t} = -\mathrm{Re}\{P^*(\vec{r},t)[\Omega_0(\vec{r},t) + \Omega_h(\vec{r},t)]\},$$
(1)

where the directional derivative is given by $\frac{\partial\Omega}{\partial\vec{k}} = (grad\,\Omega)\cdot\frac{\vec{k}}{|\vec{k}|}$, $\Omega_{0,h} = 2\tau_c(\mu/\hbar)E_{0,h}$, $E_{0,h}$ are the slowly-varying envelope of complex electric field amplitudes of the incident and diffracted waves, P is the dimensionless characteristic of complex atomic polarization, n is the inverse population of atoms, cooperative time is given by $\tau_c^2 = 8\pi T_1/3c\rho\lambda^2$, ρ is the density of resonant atoms, μ is the matrix element of the projection of the transition dipole moment, c is the light velocity.

Analytical and numerical solutions of Eqs. (1) describing the spatial-temporal dynamics of field and atomic inverse population for different schemes of diffraction geometry are studied below.

3. NONLINEAR GAP SOLITARY WAVES IN THE BRAGG GEOMETRY OF DIFFRACTION

Figure 3 illustrates the wave vectors orientation at the Bragg geometry of diffraction on crystallographic planes of photonic crystal. In linear case of light-matter interaction the well known phenomenon of total Bragg reflection takes place because of the existence of forbidden gap band of the structure. Here we show that nonlinear resonant interaction leads to the possibility of gap solitary waves propagation at the 2D geometry of diffraction as well to the formation of standing Bragg waves and coherent inverse population grating in the structure.

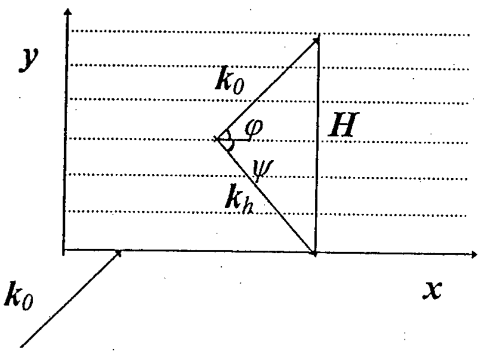


Fig. 3. The Bragg geometry of diffraction on crystallographic planes of photonic crystal.

3.1 Gap 2π-pulse. Analytical results.

The mail diffraction equations (1) can be written in the following form:

$$\begin{aligned}
&\cos\varphi\frac{\partial\Omega_0}{\partial x}+\sin\varphi\frac{\partial\Omega_0}{\partial y}+c^{-1}\frac{\partial\Omega_0}{\partial t}=\tau_c^{-2}c^{-1}P,\\
&\cos\psi\frac{\partial\Omega_h}{\partial x}-\sin\psi\frac{\partial\Omega_h}{\partial y}+c^{-1}\frac{\partial\Omega_h}{\partial t}=\tau_c^{-2}c^{-1}P,\\
&P=-\sin\theta,\\
&\theta(\vec r,t)=\int_{-\infty}^{t}\Omega_0(\vec r,t)+\Omega_h(\vec r,t)dt,
\end{aligned}\tag{2}$$

where θ is the Bloch angle, φ and ψ are the angles between wave vectors and x-axis. The simplest solution can be derived for symmetrical diffraction geometry $\varphi=\psi$ and homogeneous fields with respect to the x coordinate:

$$\frac{\partial\Omega_{0,h}}{\partial x}=0.$$

Then Eqs. (2) are reduced to the sine-Gordon equation for $\theta(y,t)$

$$(c\sin\varphi)^2\theta_{yy}-\theta_{tt}=2\tau_c^{-2}\sin\theta. \tag{3}$$

Solving the Eq. (3) we get the following exact one-soliton gap 2π-pulse solution:

$$\begin{aligned}
&\Omega_{0,h}(y,t)=\pm\frac{(1\pm u)}{2u}\Omega(y,t),\\
&\Omega(y,t)=\Omega_0+\Omega_h=2\tau^{-1}\operatorname{sech}\left[\frac{t-y/v}{\tau}\right],\\
&u=\frac{v}{c\sin\varphi},\quad v=\frac{c\sin\varphi}{(1+2\tau^2/\tau_c^2)^{1/2}},\quad \tau=\frac{\tau_c}{\sqrt{2u}}(1-u^2)^{1/2}.
\end{aligned}\tag{4}$$

Gap 2π-pulse of self-induced transparency (4) propagates at the slow velocity v along the y-direction. The angle of diffraction φ is additional parameter.

3.2 Gap solitary waves in a finite structure. Numerical results.

To study the process of formation and propagation of gap solitary waves under condition of 2D Bragg diffraction in a finite structure, the numerical simulation of a boundary problem has been carried out. We used the following form for an incident pulse

$$\Omega_0(y=0;x,t)=\Omega_0{}'(x)\,\mathrm{sech}\left(\frac{t-t_0}{\tau_0}\right),$$

$$\Omega_0{}'(x)=\frac{1}{2}\Omega_0{}''\begin{cases}1-\tanh\left(\dfrac{x-x_0}{l}\right), & x=\left(0,\dfrac{l}{2}\right),\\[2ex] 1+\tanh\left(\dfrac{x-x_0}{l}\right), & x=\left(\dfrac{l}{2},l\right).\end{cases}$$

(5)

The gap 2π-pulse is formed in the structure if amplitude and duration of the incident pulse (5) are $\Omega_0{}'=3\ 10^{13}\ s^{-1}$, $\tau_0=2\tau_c$, $\tau_c=10^{-13}$ s, and $\varphi=45^0$ (Fig. 4).

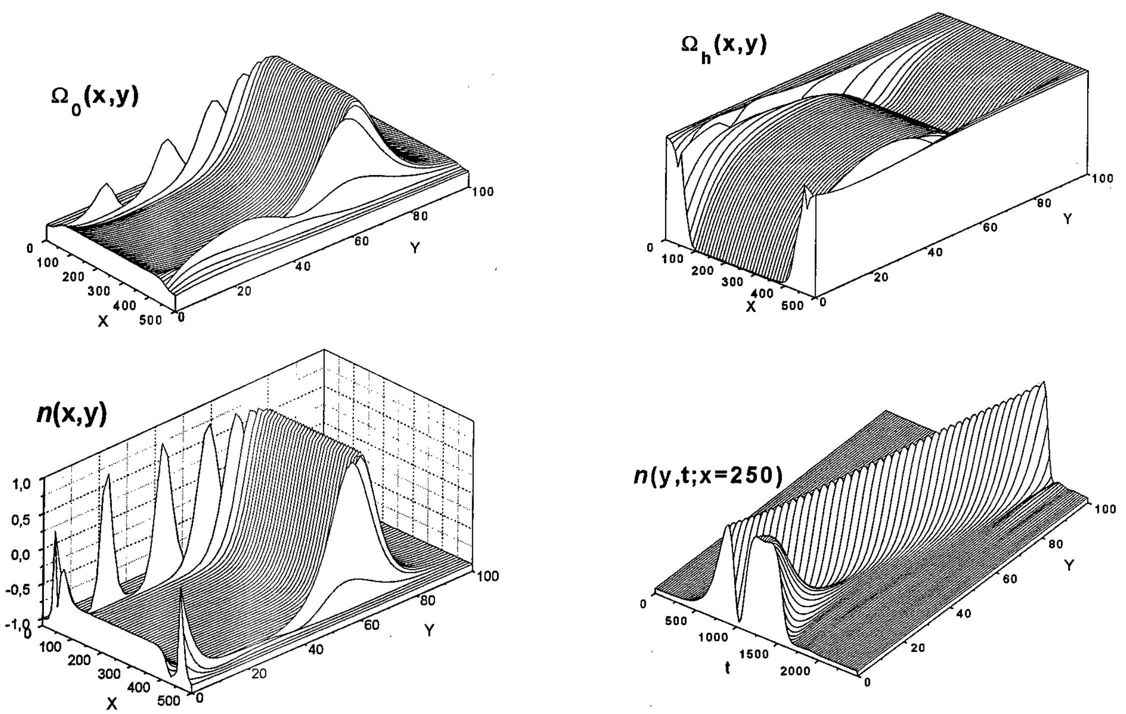


Fig. 4. Spatial distribution of the amplitudes of incident and diffracted fields and spatial-temporal dynamics of atomic inverse population in gap 2π-pulse in finite photonic crystal.

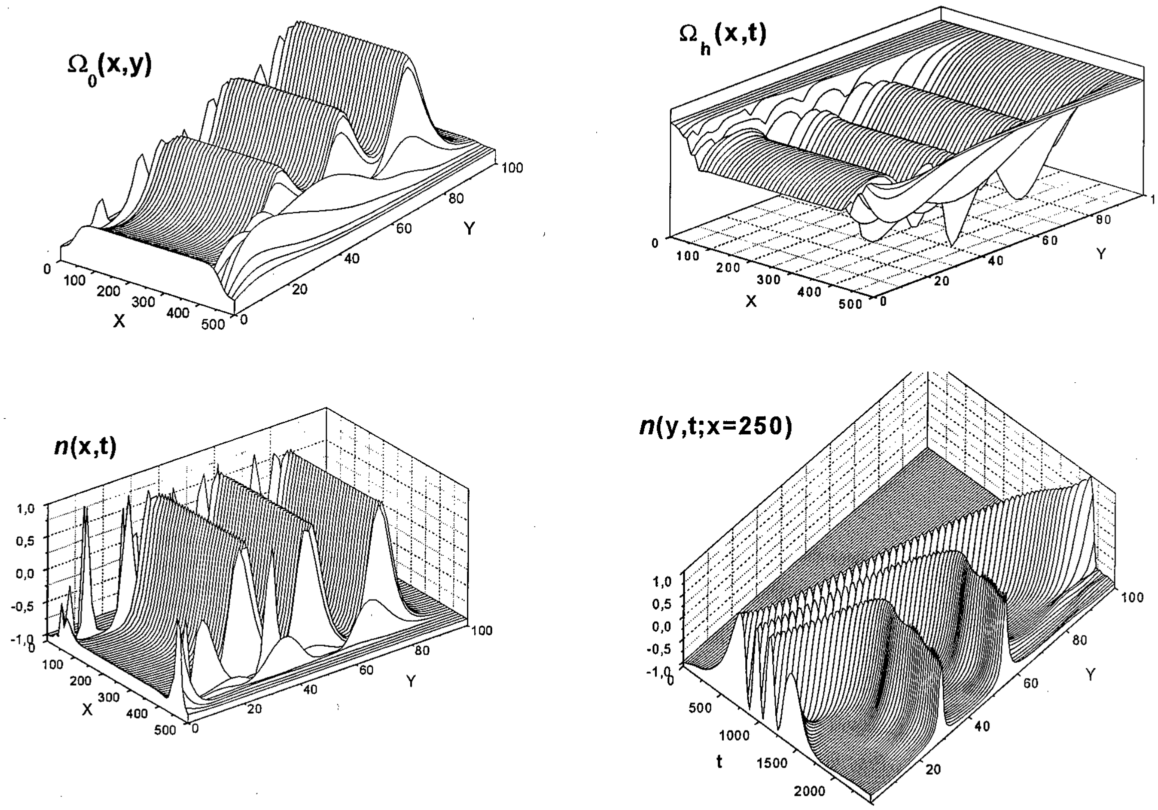


Fig. 5. Spatial and spatial-temporal dynamics of formation of atomic inverse population grating by localized standing Bragg waves. Amplitude of the incident field is large $\Omega_0{}'=5.5\ 10^{13}\ s^{-1}$, and strong light-matter interaction is characterized by short $\tau_c=5.5\ 10^{-14}$s ; $\tau_0=5.5\tau_c$, $\varphi=45^0$.

If the light-matter interaction is stronger, the cooperative time becomes shorter, and the incident pulse with enough large amplitude decays on three pulses within the structure (Fig. 5). The first pulse has enough energy to form a gap soliton-like pulse and propagates through the structure at the constant velocity (4). Other two pulses stop due to the formation of localized standing Bragg waves. Corresponding distribution of atomic inverse population represents the spatial grating of coherent inverse population. The grating slowly decays emitting light in two Bragg modes which propagate along the x-direction.

4. NONLINEAR SOLITARY WAVES IN THE LAUE GEOMETRY OF DIFFRACTION

Figure 6 shows the Laue scheme of diffraction. The incident field does not feel the total Bragg reflection near the boundary, because there is not the Bragg band gap for a field propagating in the x-direction. Two diffracted modes are coupled due to reflection on the crystallographic planes within structure. In this part of the paper we obtain exact expression for novel kind of coupled-mode soliton: Laue soliton. Computer simulation allows to investigate the process of Laue soliton formation from incident field, and furthermore, the possibility of arising of so called "0-field". This field consists of two coupled diffracted modes with opposite singes of amplitudes, so the sum of the mode amplitudes is equal to zero. As a result, the total 0-field with large partial mode amplitudes propagates through the resonant structure like linear field without nonlinear interaction with two-level atoms.

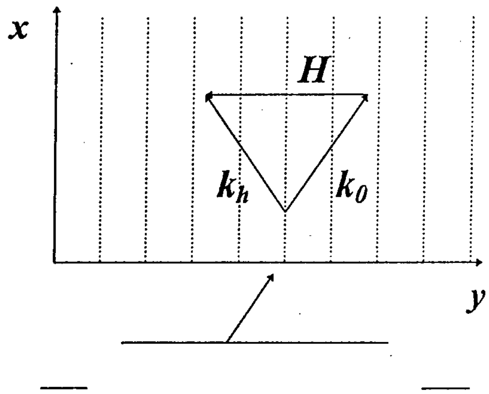


Fig. 6. The Laue scheme of diffraction on crystallographic planes of photonic crystal.

4.1 Laue two-wave soliton and "0-field". Analytical results.

Let the symmetrical diffraction scheme ($\varphi = \psi$) be realized, and fields are homogeneous with respect to the y coordinate

$$\frac{\partial \Omega_{0,h}}{\partial y} = 0.$$

Then Eqs. (2) takes the form

$$\begin{aligned} & c\cos\varphi \frac{\partial \Omega_0}{\partial x} + \frac{\partial \Omega_0}{\partial t} = \tau_c^{-2} P, \\ & c\cos\varphi \frac{\partial \Omega_h}{\partial x} + \frac{\partial \Omega_h}{\partial t} = \tau_c^{-2} P, \\ & P = -\sin\theta, \\ & \theta(x,t) = \int_{-\infty}^{t} \Omega_0(x,t) + \Omega_h(x,t) dt. \end{aligned} \tag{6}$$

It is not hard to transform from Eqs. (6) to equations for the function $\Omega = \Omega_0 + \Omega_h$

$$\begin{aligned} & \Omega = \theta_t, \\ & c\cos\varphi\, \theta_{xt} + \theta_{tt} = -2\tau_c^{-2} \sin\theta. \end{aligned} \tag{7}$$

Eq. (7) is the sine-Gordon equation and has the form like that for self-induced transparency problem in homogeneous medium. It has the following soliton solution

$$\Omega(x,t) = 2\tau^{-1} \operatorname{sech}\left(\frac{t - x/v}{\tau}\right), \tag{8}$$

$$v = \frac{c\cos\varphi}{1 + 2\tau^2 / \tau_c^2}. \tag{9}$$

The expressions (8) and (9) describe dynamics of slow soliton consisting of two diffracted waves. It is interesting to obtain solutions for each modes Ω_0 and Ω_h. Making transformation of Eqs. (6) for the function $\Omega^- = \Omega_0 - \Omega_h$, we obtain the following linear equation

$$c\cos\varphi \frac{\partial \Omega^-}{\partial x} + \frac{\partial \Omega^-}{\partial t} = 0. \tag{10}$$

The solution of Eq. (10) is just a linear wave

$$\Omega^- = \Omega^-(\xi = x - c\cos\varphi\, t)$$

which propagates in the structure at the fast velocity $c\cos\varphi$.

This result looks surprising, because the sum of two diffracted modes Ω moves as a soliton at the slow velocity (9), but the difference Ω^- has the fast velocity $c\cos\varphi$. It is possible only in the cases if Ω or Ω^- is equal to zero.

Let us to consider the first case, when the field sum is not equal to zero but the difference is zero

$$\Omega^- = \Omega_0 - \Omega_h = 0,$$
$$\Omega = \theta_t \neq 0.$$

It means that amplitudes of two modes are equal each other. Using formula (8), we obtain the following solutions for both waves:

$$\Omega_0 = \Omega_h = \frac{1}{2}\Omega = \frac{1}{\tau}\operatorname{sech}\left(\frac{t - x/v}{\tau}\right). \tag{11}$$

This is two-wave Laue soliton, or Laue 2π-pulse, coupling two diffracted modes with equal amplitudes.

Another case is realized when the field sum is zero but the difference is not equal to zero:

$$\Omega = \Omega_0 + \Omega_h = 0, \quad \theta = 0,$$
$$\Omega^- = \Omega_0 - \Omega_h \neq 0,$$

hence

$$\begin{aligned} &\Omega_0 = -\Omega_h, \\ &\theta = 0, \quad v = c\cos\varphi. \end{aligned} \tag{12}$$

We have called the linear solution (12) "0-field" because it is characterized by the sum Ω=0, and propagating through the structure, it does not interact with resonant atoms (θ=0), even if the amplitude of each diffracted mode is rather large.

4.2 Laue solitary waves in a finite structure. Numerical results.

Now it is time to put a question, is it possible to excite the Laue soliton (11) and 0-field (12) within a finite photonic crystal by outside incident field? To answer the question we have solved a boundary problem by means of numerical integration of Eqs. (1). The following form of incident pulse has been used:

$$\begin{aligned} &\Omega_0(x = 0; y, t) = \Omega_0'(y)\operatorname{sech}\left(\frac{t - t_0}{\tau_0}\right), \\ &\Omega_0'(y) = \frac{1}{2}\Omega_0'' \begin{cases} 1 - \tanh\left(\dfrac{y - y_0}{l}\right), & y = \left(0, \dfrac{l}{2}\right), \\ 1 + \tanh\left(\dfrac{y - y_0}{l}\right), & y = \left(\dfrac{l}{2}, l\right). \end{cases} \end{aligned} \tag{13}$$

Figure 7 illustrates the result of numerical simulation of nonlinear Laue diffraction of the incident pulse (13) in finite photon crystal when pulse amplitude Ω_0'=2 10^{13} s^{-1}, pulse duration τ_0=0.3τ_c, τ_c=3 10^{-13} s, and φ=30^0. The Laue soliton and 0-field are formed within the structure. Their parameters (the sign and the value of mode amplitudes, velocity and duration) agree with analytical results (11) and (12). Fast 0-field outstrips the slow Laue soliton and does not

excite resonant atoms. Figure 8 shows the spatio-temporal dynamic of the Laue soliton and 0-field formation and propagation.

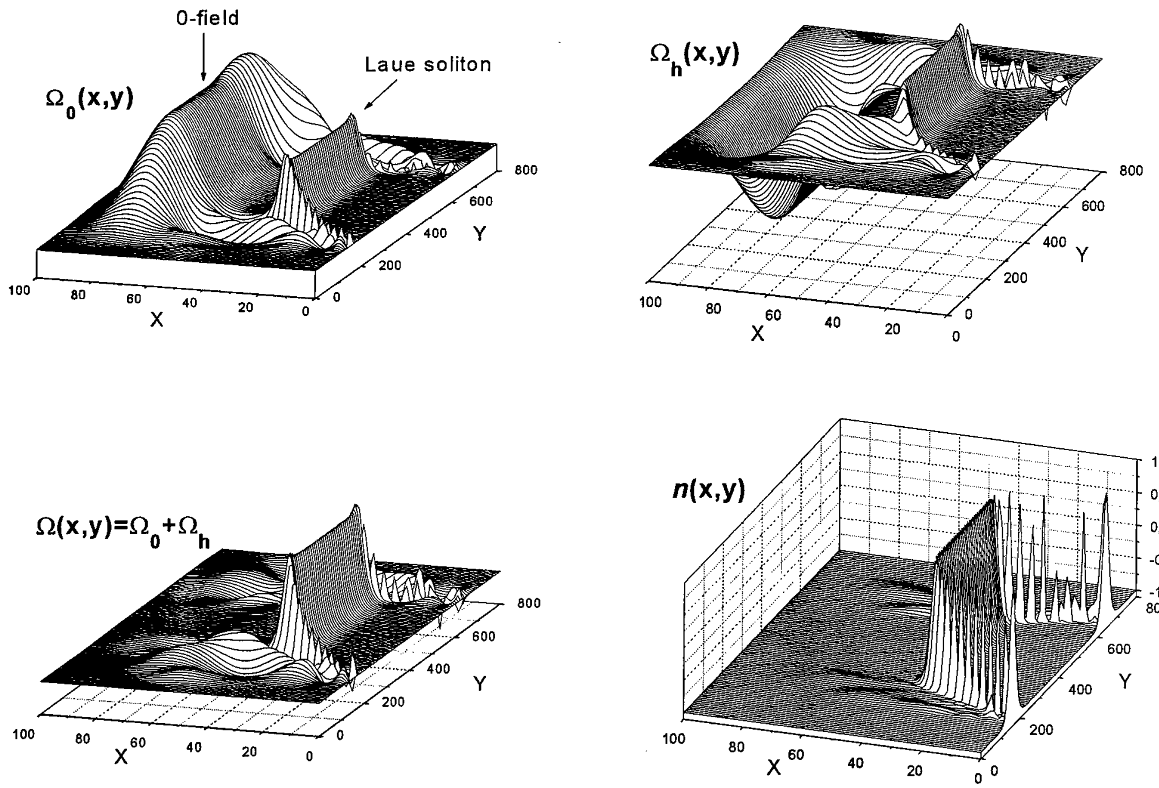


Fig. 7. The Laue soliton and 0-field pulse. Spatial distribution of two diffracted modes of field and inverse population of atoms in the structure.

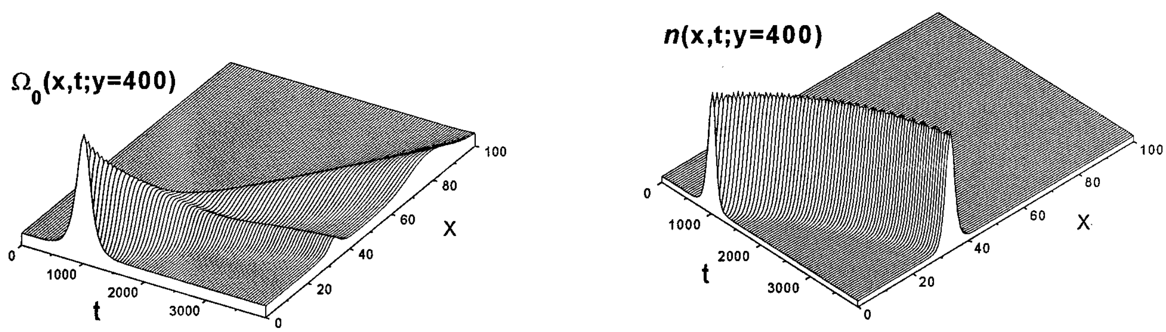


Fig. 8. The Laue soliton and 0-field pulse. Spatio-temporal dynamics of one mode of field and inverse population.

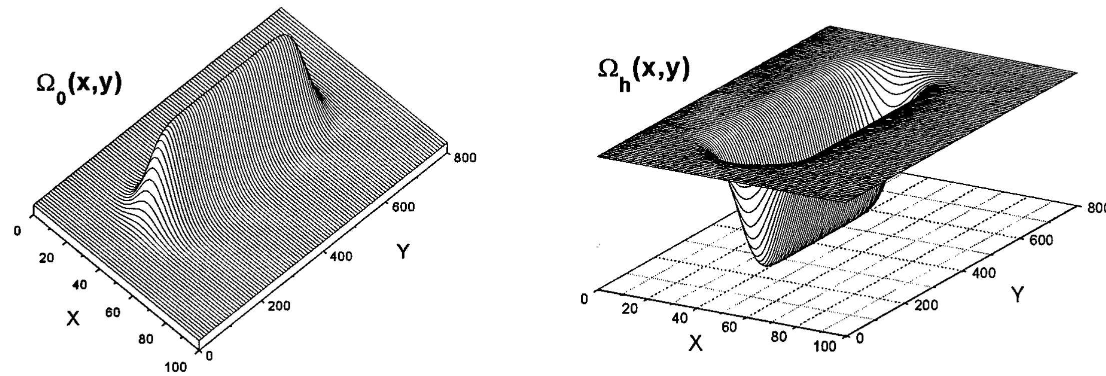


Fig. 9. The 0-field pulse. Spatial distribution of diffracted modes of field when $\Omega_0'=2\ 10^{13}\ s^{-1}$, $\tau_0=3.3\,\tau_c$, $\tau_c=3\ 10^{-14}$ s, and $\varphi=30^0$.

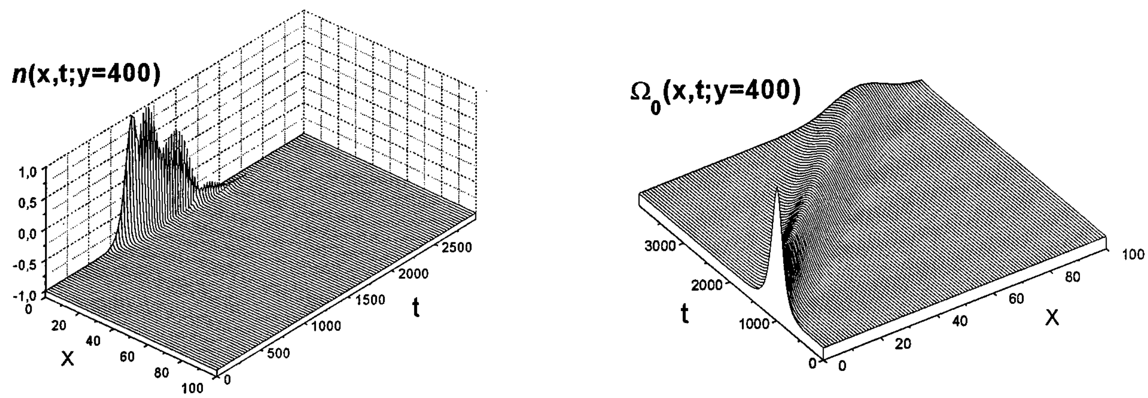


Fig. 10. Spatial-temporal dynamics of inverse population of atoms and one mode of field in the process of 0-field formation and propagation.

In the case of strong light-matter interaction (short $\tau_c=3\ 10^{-14}$s), only 0-field pulse arises (Fig. 9). Note that although the 0-field consists of linear waves, it is formed due to strong nonlinear interaction of incident field with resonant atoms near the structure boundary. In Fig. 10, we can see the large value of inverse population of atoms near the boundary $x\approx0$.

5. CONCLUSION

The developed above theory of nonlinear two-wave Bragg diffraction of coherent light in a resonant multidimensional photonic crystal allows to predict a number of novel kinds of nonlinear solitary waves: the Laue soliton, 0-field, propagating and standing gap solitary waves. These phenomena could be observed experimentally , for instance, in an opal 3D photonic crystal with embedded dye molecules[10] or in 2D structure of air-rods filled with dye solution[8].

6. ACKNOWLEDGMENTS

The authors are grateful to Professor A. Andreev, Professor C. Bowden, and Professor J. Haus for useful discussions. This work was supported by the ERO of the USA, by the Russian Foundation for Basic Research, and in part by the Russian Universities Foundation.

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TWO-COMPONENT SUPERRADIANCE SCHEME OF γ-LASING

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It is well known that the lack of the pumping sources of required intensity is one of the main difficulties in developing of the γ-laser scheme based on the nuclei with lifetime of about 10 μs or smaller. Recently [1,2] it was shown that the dynamics of the two-component superradiance (SR) is significantly different from that for monocomponent superradiative media. Specifically the delay time of the two-component SR can exceed the SR pulse temporal width for a few order of magnitude. It is the SR delay time that determines the duration of pumping. Therefore the adoption into the active media of γ-laser the second resonantly absorbing component can significantly weaken the requirements for the intensity of pumping.

The two-component active medium consists of the nuclei of the two species. The nuclei have resonant or quasiresonant radiative transitions ($\omega_b = \omega_a + \Delta$, $|\Delta| << \omega_a$, ω_b) and differ in the value of radiative lifetime $\tau_{sp}^{(a,b)}$. The nuclei with the short lifetime $\tau_{sp}^{(b)} < \tau_{sp}^{(a)}$ will be called by fast component and the nuclei with the long lifetime in the resonant transitions will be called by slow component. It is assumed that the slow component is excited into the upper state of the resonant transition by some source of external pumping. The second component is initially in the low state of the resonant transitions that should be the ground or metastable state.

The superradiative decay of the two-component active medium results in the emission of the coherent pulse of γ-radiation. The parameters of SR pulse depend essentially on the ratio of concentrations (r_0/R_0) of slow (R_0) and fast (r_0) components. The results of the computer simulations show that the increase of the concentration of the resonantly absorbing component results in the increase of the SR peak pulse intensity and delay time, while the pulse temporal width decreases. There is some threshold value of the ratio $(r_0^{(th)}/R_0)$. The SR emission terminates when the concentration of the resonantly absorbing component exceeds the threshold value $(r_0^{(th)})$. We discuss the dependency of threshold concentration on the active medium parameters.

It is not necessary to have the exact resonance between the two components. The results of the computer simulations show that there is an optimal detuning between the component transitions frequencies ($\Delta = \omega_b - \omega_a$). We discuss the dependency of the SR pulse parameters on the detuning (Δ) and active medium parameters.

It was shown [1] that in the two-component media the regime of inversionless SR is possible. In this case the concentration of the fast resonantly absorbing component exceeds that for slow component. The inversionless SR is characterized by the highest value of the delay time. Thus this regime is the most promising for γ-lasing.

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COHERENT INTERACTIONS IN THREE-LEVEL MEDIUM: PHASE-MODULATED SIMULTON AND RAMAN SOLITON, EXPERIMENTAL CRITERION FOR COOPERATIVE RAMAN SCATTERING

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U.S.Army Missile Command, Weapons Sciences Directorate Research, Development and Engineering Center, Redstone Arsenal, AL 35898-5248 USA

The coherent interaction of the bichromatic field with a system of three-level atoms is considered. The new solutions of this problem corresponding to phase-modulated simulton and Raman soliton have been found in analytical form. It is shown that the Stokes pulses of cooperative and stimulated Raman scattering have the different spectra. Both results are of great interest for interpreting the results of relevant experiments.

COHERENT INTERACTIONS IN THREE-LEVEL MEDIUM: PHASE-MODULATED SIMULTON AND RAMAN SOLITON, EXPERIMENTAL CRITERION FOR COOPERATIVE RAMAN SCATTERING

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There is a growing interest in the studies of the resonant Raman scattering in the molecular systems in the last decade. This interest is twofold and due to the progress in the generation of the ultrashort pulses of FIR emission and the lack of the theory adequately explaining the dynamics of the Raman soliton formation. The lower pressure molecular gases are the most significant class of the active media for the coherent FIR sources. These media are the narrow band systems, therefore the nonlinear coherent processes such as superradiance (SR), cooperative (CRS) and stimulated (SRS) Raman scattering play a decisive role in the pulse generation, amplification and propagation.

We report here the results of the theoretical study that enable us to determine the form of solitary pulses at adjacent transitions of a three-level atom or molecule at arbitrary ratio of the oscillator strengths. The conditions under which the simultons and Raman solitons arise in the Λ and V scheme in resonant and off-resonant cases are discussed in detail. These conditions depend on the of oscillator strengths at the adjacent transitions, frequency detuning and amplitude of the pumping pulse in the case of Raman soliton. Since the profiles of the solitary pulses are described in analytical form, this can be extremely useful in studying the properties of solitonlike excitations observed in various experiments.

The results of the computer simulations on the resonant Raman scattering in three-level medium enable us to determine conditions for the optimal conversion of the frequency and shape of pulses. The study of the temporal spectra of the Stokes pulses has shown that the detuning of the pumping pulse from the exact resonance allows to distinguish the SR, CRS and SRS processes. This feature is illustrated in Fig.1 where the temporal spectra of the Stokes pulse are shown for different molecular gas pressure. We can see that for the dimensionless pressure $p<1$ the spectrum is symmetric. This region of pressure corresponds to SR emission. For CRS process ($1<p<4$) the shift of the pulse carrier frequency is opposite to the detuning of the pumping pulse, $\Delta_p = 2$. For SRS process ($p>4$) the shift coincides with the detuning.

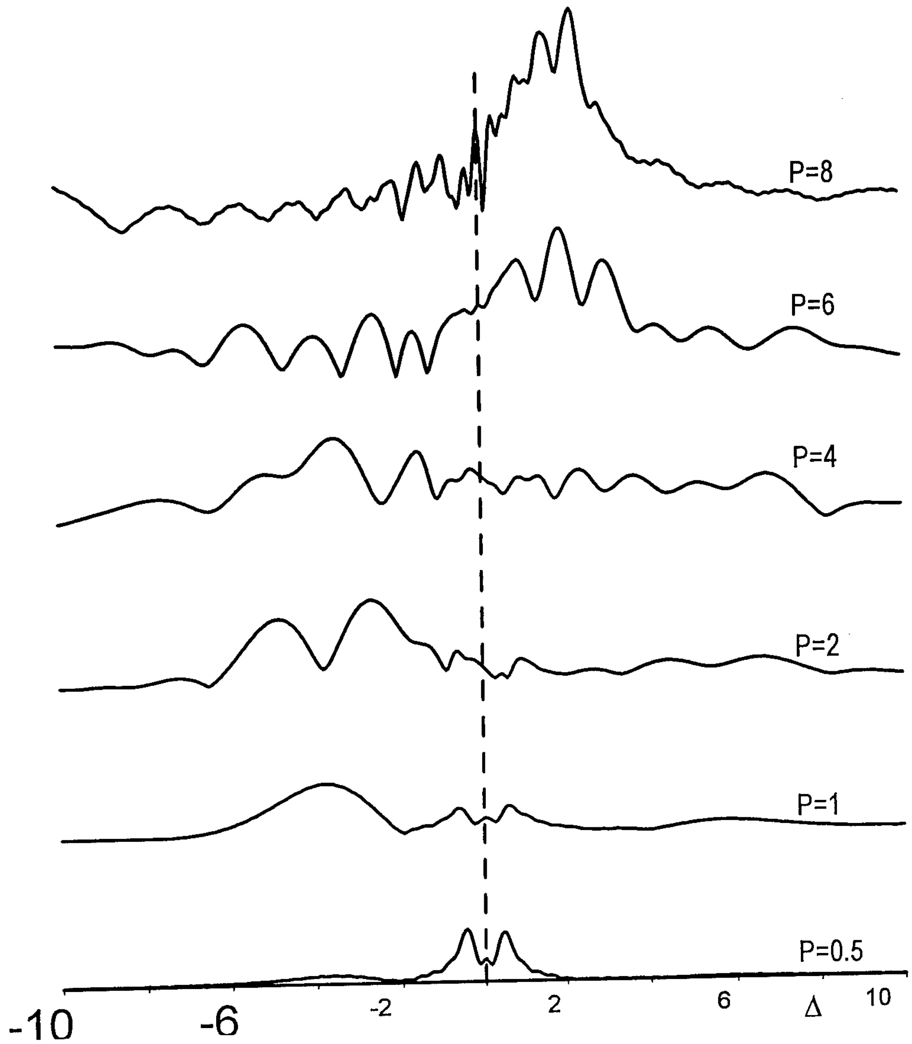

FIGURE CAPTION

Fig.1. The power spectrum of the Stokes pulse for the different gas pressure p, the pulse carrier frequency ω coincides with the frequency of the Stokes transition $\omega = \omega_{32}$, when $\Delta = 0$.

TECHNICAL DIGEST

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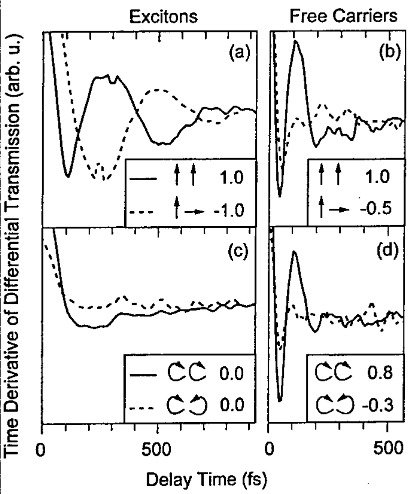

QWE7 **Fig. 3.** Excitonic (a and c: $E_{det} = 1.500$ eV) and free-carrier (c and d: $E_{det} = 1.530$ eV) HH-LH quantum beats measured in spectrally and time-resolved pump-probe experiments. The time derivative of the transmission change is plotted versus delay between pump and probe. Inserts: applied polarizations of pump and probe pulses plus theoretically predicted relative amplitudes of the oscillations (numbers).

HH-LH quantum beats are important in spectrally resolved pump-probe signals even close to the absorption edge.

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QWE8 — 9:45 am

Ultrafast adiabatic population transfer in p-doped semiconductor quantum wells

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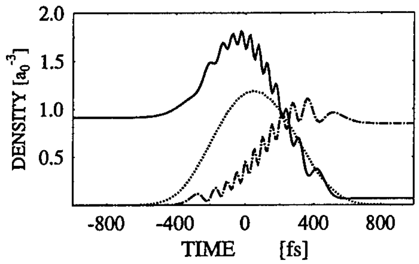
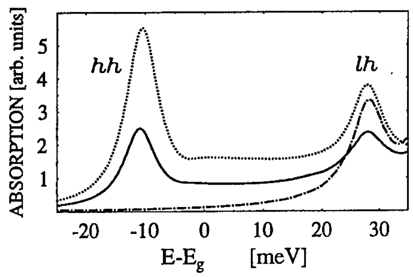
In atomic and molecular physics, coherent optical techniques allowing for almost complete ultrafast transfer of a population between different molecular eigenstates has been developed and refined for many years.[1–3] One particularly successful scheme is called stimulated Raman scattering by delayed pulses (STIRAP). Within this scheme, it is possible to transfer a population between two nonoptically coupled states by using a third state (which is optically coupled to both the initial and the final state) without actually occupying it, in the end, at all.

As for semiconductors, the question arises whether similar techniques can be used to transfer, for example, holes from the heavy-hole (HH) band to the light-hole (LH) band without creating electrons in the process. We have studied this problem theoretically and have identified parameter regimes where we believe the delayed-pulse scheme can be efficiently applied to the HH-LH population transfer.



QWE8 **Fig. 1.** Density versus time for the HH density (solid line), LH density (dash-dotted line), and conduction-band density (dotted line). The unit length is $\alpha_0 = 135$Å. The optical pulses are far detuned from the exciton resonances, and their duration is 400 fs (FWHM in intensity).



QWE8 **Fig. 2.** Linear optical absorption spectra, including HH and LH exciton resonances: nondoped quantum well (dotted line), doped quantum well before (dash-dotted line), and after (solid line) the adiabatic transfer.

The theory is built of similar elements as the one used to study dark states in semiconductors.[4] It involves a numerical solution of the equation-of-motion for the interband polarizations and intraband populations within an appropriate six-band model. It takes into account the Coulomb interaction and, thus, linear and nonlinear exciton effects.

As an example, we show in Fig. 1 the density response of one (of the two degenerate) HH band, one LH band, and one conduction band for optimized light-field parameters including 400-fs pulses far detuned from the exciton resonances. In the calculation, the other three bands are also taken into account. However, due to optical selection rules, they are completely off-resonant and do not yield the transfer characteristics shown in Fig. 1. The initial HH density is due to p-doping. The absorption spectra for the nondoped quantum well, and for the doped quantum well before and immediately after the population transfer, are shown in Fig. 2. In our calculations the population transfer has an almost dramatic effect on the spectrum: it creates the HH exciton at the expense of the LH exciton. This feature could prove to be useful in ultrafast optical switching applications.

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QWF — 1:00 pm–2:30 pm

Exhibit Hall

Poster Session: II

QWF1

Nonlinear solitary waves in two-and three-dimensional resonant periodic structures

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The study of the nonlinear interactions in periodic structures has gained considerable interest in the past few years.[1] This is due to the finding of the novel kind of nonlinear solitary waves that are propagated at Bragg frequency within the linear forbidden gap band of the periodic medium. It has been shown that gap solitons and oscillating solitary waves exist in one-dimensional structures with resonant[2] and Kerr[3] nonlinearity. These waves are formed by two counterpropagating coupled Bragg modes. Here we investigate theoretically the dynamics of formation and propagation of nonlinear solitary waves in the general case of two-wave diffraction problem in two- and three-dimensional periodic resonant structures. The vector Bragg condition $\boldsymbol{k_h} = \boldsymbol{k_0} + \boldsymbol{H}$ for the wave vectors $\boldsymbol{k_0}$ and $\boldsymbol{k_h}$ of the incident and diffracted waves and the reciprocal lattice vector $\boldsymbol{H}$ is to be satisfied in this problem.

The equations of two-wave nonlinear dynamic diffraction have been derived from the semiclassical Maxwell-Bloch equations describing the coherent light-matter interaction under the Bragg condition. By means of analytical and numerical integration of the equations, we investigated the process of formation and propagation of Bragg solitary waves for the different geometric schemes of diffraction. It has been shown that nonlinear solitary waves appear both in the case of Bragg geometry of diffraction, such as gap two-wave solitons, and in the case of Laue geometry of diffraction, such as two-wave solitons of nonlinear Bormann effect. The "Laue soliton" propagates in the direction of the normal to reciprocal lattice vector. The numerical simulation of the diffraction process has provided the possibility of studying the wave dynamics in a finite medium under different boundary conditions.

This work was supported by the European Research Office of the U.S. Army, Contract No. 68171-97-M-5698, and by the Russian Foundation for Basic Research, Grant No. 96-02-19285.

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ThW28

COUPLED PULSES PROPAGATION IN A TWO-COMPONENT MEDIA

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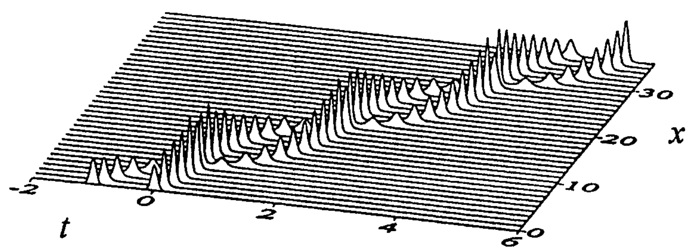
We report the results of the study on coherent pulse propagation in a two-component medium consisting of two species of resonant atoms. As the Raby frequency is proportional to the dipole matrix element of transition ($\Omega \sim d$), we have $\Omega_a < \Omega_b$ as far as $d_a < d_b$. So we call the "a" atoms as slow atoms, and "b" atoms as fast atoms.

It is well known that the ultrashort pulse evolution depends on its area in the coherent mode for both resonantly amplifying and resonantly absorbing media. In the two-component medium the propagating pulse has different area with respect to slow and fast atoms [1]. Therefore the 2π-pulse with respect to the fast atoms will be amplified when the slow atoms are in the excited state and will be absorbed when the slow atoms are in the ground state. We consider the subthreshold regime [1] and show that the regime of coupled pulses propagation can occur in this case. We obtained that two pulses in the two-component medium can be bound in pair and begin to propagate as an unified excitation. The intensity and duration of the coupled pulses oscillate near some mean values.



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ThW29

OPTICAL SCREW-TYPE TRANSPARENCY

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We present a new exact solution of Maxwell-Schrodinger set of equations. This describes propagation of a bichromatic laser pulse through a lambda-type medium where the initial atomic state is prepared in the form of spatially-varying coherent superposition of low-energetic states. The common envelope $E =\sqrt{E_1^2 + E_2^2}$ behaves as a usual 2π hyperbolic secant pulse, but the ratio between the components changes due to coherent Raman scattering so $\mbox{arc tg} \frac{E_2}{E_1} = Gz$, where z is the coordinate, G is the constant determined by both the incident pulse parameters and the initial coherence between the atomic states. Our solution demonstrates a direct connection of electromagnetically induced transparency in adiabatic regime to the self-induced transparency effect. We regard this solitary wave as a screw-type one because its propagation requires matching between incident pulse parameters and initial coherency (the latter can be prepared by means of CW coherent population trapping).

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Recent Developments in Local Field Effects in Nonlinear and Quantum Optics

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Effects of Lorentz-Lorenz local fields are manifest in matter-laser field interactions where the density of the medium is such that there are, on the average, many atoms or molecules within some cubic resonance wavelength. The local field-atom interaction is reviewed from the microscopic, semi-classical approach. Some important and novel results of the formulation and predictions for corresponding experimental observations are reviewed. These include recently experimentally observed intrinsic optical bistability, the spectral red shift in the ground state of a two-level system, and the more recently observed excitation dependent spectral shifts and line narrowing. Each of these phenomena are discussed in relation to theoretical prediction and experimental observation. The results of these experiments and their close agreement with theoretical predictions provide impetus for further experimental investigations of important novel predicted, but as yet unobserved effects of local fields. These include, a) enhancement of refractive index and gain in lasing without inversion [1] (LWI); b) nonlinear effects in electromagnetic field induced transparency (EIT); c) piezophotonic and magnetophotonic switching [2]; d) intrinsic adiabatic inversion [3]; e) intrinsic strong self phase modulation in self induced transparency [4] (SIT). These novel predicted phenomena are discussed in connection with aspects of approach to experimental observations.

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9:30
FC3
(Invited)

NEW TYPES OF COOPERATIVE LIGHT-MATTER EXCITATIONS IN MULTICOMPONENT AND MULTILEVEL MEDIA

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Solitons in the excited two-level medium of finite length. The solutions of the Maxwell-Bloch equations have been found for the case of two-level extended medium of finite length. In contrast to the solitons of the infinite medium in this case the solutions have the non-local form, as a result the soliton shape is transformed when pulse passes through the medium boundary. Another specific feature is that if the atomic system is initially in the ground state then the medium excitation propagates along with the optical pulse. In the initially excited medium the optical pulse inside the medium and the medium excitation propagate in the direction opposite to the incident pulse.

Pulse propagation in two-component media. The two-component media consists of the mixture of the two-level atoms with the different dipole matrix elements of the resonant transitions. The soliton solutions have been found for the different initial states of the components. The specific type of the collective light-matter excitations appropriate to the two-component media are the pulses of stationary area. If the slow component is excited initially and the fast component is in the ground state the incident pulse can be amplified without changing its area. The pulse amplitude increases and its temporal width decreases with the travelled distance. The efficiency of amplification depends on the component concentration and can be significantly higher than that in the monocomponent medium of the excited atoms alone. The pair of the incident pulses can propagate in the two-component medium as an unified excitation. In dependent on the initial distance between the pulses they can propagate as an oscillating, colliding or solitary pulse pair.

Solitons of three-level media. It has been shown that the possibility of exciting of the self-similar pulses in the adjacent transitions is determined by the square root of oscillator forces ratio (α). At the exact resonance the simultons of the Λ- scheme occur in the case when α is an integer. In this case the pulse in strong transition has a few maxima, the number of which is equal to α. The Raman solitons exist at any arbitrary value of α. The number of deeps in the dark soliton is determined by the whole part of α. For the Λ- scheme the off-resonant simultons and Raman solitons are phase-modulated.

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QThG8

Spatio-temporal nonlinear dynamics of coherent field in periodic resonant structures and gain gratings

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Interest in nonlinear light-matter interaction in distributed feedback structure has considerably grown in the last years [1]. The nonlinear spatio-temporal dynamics of the field in the periodic structures is qualitatively different from that both for the case of linear Bragg diffraction and the nonlinear interaction outside the diffraction condition. It has been predicted earlier[2] that gap soliton of self-induced transparency propagates at the Bragg frequency in discrete resonant structure, which consist of a set of ultrathin layers of two-level atoms.

Here we consider theoretically the short pulse transmission in a resonant one-dimensional Bragg structure with arbitrary periodic modulation of atomic density. This model could be realized, for instance, in experiments with colloidal crystals[3]. We present analytical and numerical solutions of Maxwell-Bloch equations, which describe the spatio-temporal dynamics of formation and propagation of gap solitary waves within the linear forbidden frequency gap band of arbitrary resonant periodic Bragg structure. The velocity and the form of the pulse depends on the profile of atomic density modulation. The pulse propagation in sinusoidal structure is similar to the case of discrete structure.

We studied also the coherent decay of optically-written sinusoidal gain grating under Bragg condition. Describing this process by numerical solution of coupled-mode Maxwell-Bloch equations we investigated the dependence of the spatio-temporal dynamics of field and inverse population of atoms on frequency shift and initial inverse population. The coherent interaction of incident pulse with the gain grating leads to its amplification and shortening.

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QThG9

POLARIZATION-PHASE DYNAMICS IN A FOUR-FREQUENCY ANISOTROPIC-CAVITY RING CLASS-A GAS LASER

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Ring gas lasers (RGL) with anisotropic cavities represent an appropriate model to study polarization dynamics in multi - mode systems, because even in the case of single-longitudinal-mode operation there are four waves above the threshold with different intensities, frequencies and states of polarization [1-3]. Another factor which is inherent in RGL (unlike standing-wave ones) is the determining role of the phase characteristics of the emitted field on laser operation.

On the basis of the Jones vectors and matrices formalism under the assumption that a reflecting element is placed inside the cavity and the boundary conditions for electromagnetic field on this element are taken into account, a model has been developed of a single-longitudinal-mode (four-frequency) ring gas laser with anisotropic cavity [4].

Temporal evolution of intensities of four running waves and phase differences between counterrunning waves are described by the system of six nonlinear first order differential equations. The equations of motion are valid in the third order of the field perturbation theory at adiabatic elimination of material variables for arbitrary type of cavity anisotropy and arbitrary transitions between the working levels in the presence of a longitudinal magnetic field on the active medium. Comparatively to previous studies, restricted, as a rule, by linear polarization of the emitted field, (see, for example,[1]), the present model takes into account the deformation of the state of polarization by the active medium. Coefficients of backscattering which determine the width of a frequency locking zone, depend on polarization parameters of counterrunning waves. They reach their maximum values at linear polarization and equal to zero at circular polarization.

In the absence of any time-dependent external influence spontaneous pulsations of intensities of the orthogonally polarized counterrunning waves, antiphase in their nature, and phase differences of these waves have been revealed in a wide region of detunings and coefficients of backscattering for different types of the cavity anisotropy. Polarization switches of intensities of orthogonally polarized counterrunning waves and jumps of the phase differences between these waves on π have been found at crossing the line center tuning.

Comparison with known experimental results [3] has shown the adequacy of the model proposed.

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10.30 QWA9

Nonlinear Bragg diffraction and solitary waves in multidimensional resonant periodic structures

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The study of the nonlinear interactions in periodic structures has gain considerable interest in the past few years[1]. This is due to the finding of the novel kind of nonlinear solitary waves which are propagated at Bragg frequency within the linear forbidden gap band of the periodic medium. It has been shown that gap solitons and oscillating solitary waves exist in one-dimensional structures with resonant[2] and Kerr[3] nonlinearity. These waves are formed by two counterpropagating coupled Bragg modes. Here we investigate theoretically the dynamics of formation and propagation of nonlinear solitary waves in the general case of two-wave diffraction problem in 2D and 3D periodic resonant structures. The vector Bragg condition $\boldsymbol{k_h} = \boldsymbol{k_0} + \boldsymbol{H}$ for the wave vectors $\boldsymbol{k_0}$ and $\boldsymbol{k_h}$ of the incident and diffracted waves and the reciprocal lattice vector $\boldsymbol{H}$ is to be setisfied in this problem.

The equations of two-wave nonlinear dynamic diffraction have been derived from the semiclassical Maxwell-Bloch equations describing the coherent light-matter interaction under Bragg condition. By means of analytical and numerical integration of the equations we investigated the process of formation and propagation of Bragg solitary waves for the different geometric schemes of diffraction. It has been shown that nonlinear solitary waves appear both in the case of Bragg geometry of diffraction like gap two-wave solitons and in the case of Laue geometry of diffraction like two-wave solitons of nonlinear Borrmann effect. The "Laue soliton" propagates in the direction of the normal to reciprocal lattice vector. The numerical simulation of diffraction process has given the possibility to study the wave dynamics in a finite medium under different boundary conditions.

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10.45 QWA10

PULSE PAIR PROPAGATION IN TWO-COMPONENT MEDIA

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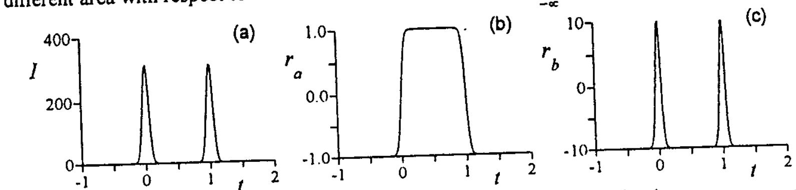
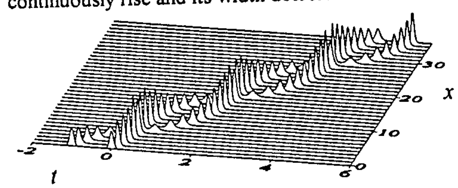
We report here the results of computer simulations on the coherent pulse propagation in the two-component medium. Two-component medium consists of two species of the resonant atoms which differ in the value of the dipole moments of the resonant transitions ($d_b > d_a$). It is well known that the Raby frequency is proportional to the dipole matrix element of transition ($\Omega \sim d$). Hence $\Omega_a < \Omega_b$ and we shall call the "a" atoms as slow, and the "b" atoms as fast.

The theory shows that the dynamics of pulse propagation in the two-component media depends primarily on the value of the parameter $\gamma = (|d_a|^2 r_a)/(|d_b|^2 r_b)$, where r_a (r_b) is the concentration of the slow (fast) atoms. We consider the subthreshold regime: $\gamma < 1$. It is well known that the ultrashort pulse evolution in the resonant media depends significantly on the area of the incident pulse θ. In the two-component medium the incident pulse has the different area with respect to the slow and fast atoms $\theta_{a,b} = \int_{-\infty}^{\infty} \Omega_{a,b}(t)\,dt$



We study the dynamics of propagation of two pulses (Fig.1a) in the two-component medium. It is assumed that the fast and slow atoms are initially in the ground state and that area of each incident pulse with respect to the slow atoms is equal to π ($\theta_a = \pi$). In the case $d_b = 2d_a$ the pulse area with respect to the fast atoms is twice larger: $\theta_b = 2\pi$ (Fig.1bc). The first pulse in pair propagates in the absorbing medium, it loses its energy by exciting the slow atoms of the two-component medium. The pulse is broadened and decreases in intensity. The second pulse transfers the excited slow atoms into the ground state. The pulse intensity continuously rise and its width decreases. The velocity of the second pulse which propagates in the amplifying medium is higher than velocity of the first one and after some time the pulses are changed in their places. Therefore this two pulses combine into the pair in two-component medium and begin to propagate as an unified excitation. The Fig.2 shows the spatio-temporal dynamics of bound pulses in the two-component medium. We can see that the bound pulses are changed their places in the process of propagation and the dynamics of the system repeats itself periodically. We can see that the bound pulses overtake each other and their amplitudes and temporal widths oscillate near some average values.



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